PRECESSION INJECTION IN THE DELFT ISOCHRONOUS CYCLOTRON

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Summary

External injection of particles into an isochronous cyclotron using the precession motion along a hill-valley boundary, has been realised in the Delft 12 MeV isochronous cyclotron. Proton beams of 100μA are accelerated up to extraction radius with injected beams of between 1 and 2 mA at 200 keV. At the central region a gradual coupling between precession motion and central motion is brought about by a newly shaped magnet field in the central region and the electric field of a straight accelerating gap. Results of field measurements and shadow measurements are given. There are no discrete deflection structures present in the central region.

Introduction

The precession motion along a hill-valley boundary of the magnetic field of an isochronous cyclotron has been described as a means of external injection of ion beams.[1,2] As we studied the beam trajectories and the vertical stability of the precession motion for a cyclotron with machine parameters which are common at present, it became clear that the problem to be solved lay in the central region. Due to the decreasing magnetic field flutter with smaller radii, a beam entering the central region in the precession mode will show decreasing precession velocity and decreasing vertical stability at such a rate, that normally a beam will be vertically spilled before reaching the central region.

A new magnet configuration

We found a solution in the concept of gradual transition in phase space. If the dimensions of the volume occupied by the beam in phase space can be kept low, a good transmittance might be expected.

One of the outstanding features of an isochronous cyclotron is its continuous operation, so one is limited in his choice of parameters which may affect a transition. A good parameter seemed to be the energy of the beam which increases while the cyclotron system as a whole remains the same.

To realise a system which would show a gradual transition of the motion, we devised a new magnet configuration in the cyclotron central region(fig. 1 and 2). In this configuration a hill valley boundary, along which the precession motion should take place, is extended into the central region, which has been realised by adding iron over roughly 180 degrees for small radii, and by cutting off part of the pole tips of opposite hills. For larger radii the normal pole shape is resumed.

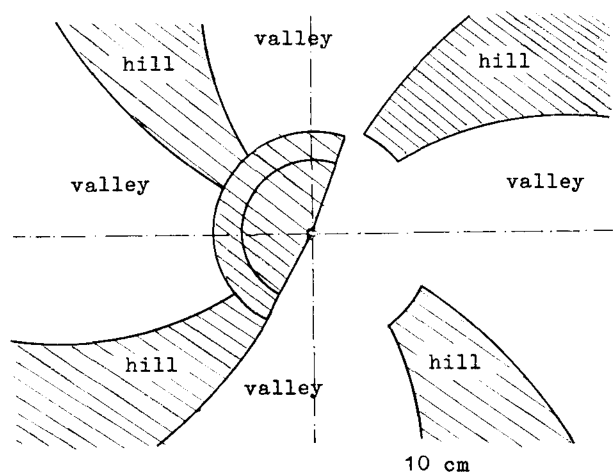

Fig. 1. A sketch of the new pole contours in the central region.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 254-259

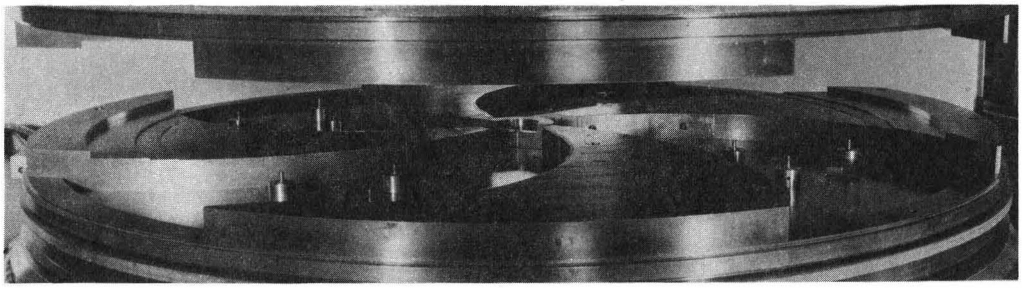

Fig. 2. Photograph of the magnet poles with the new pole configuration in the central region.

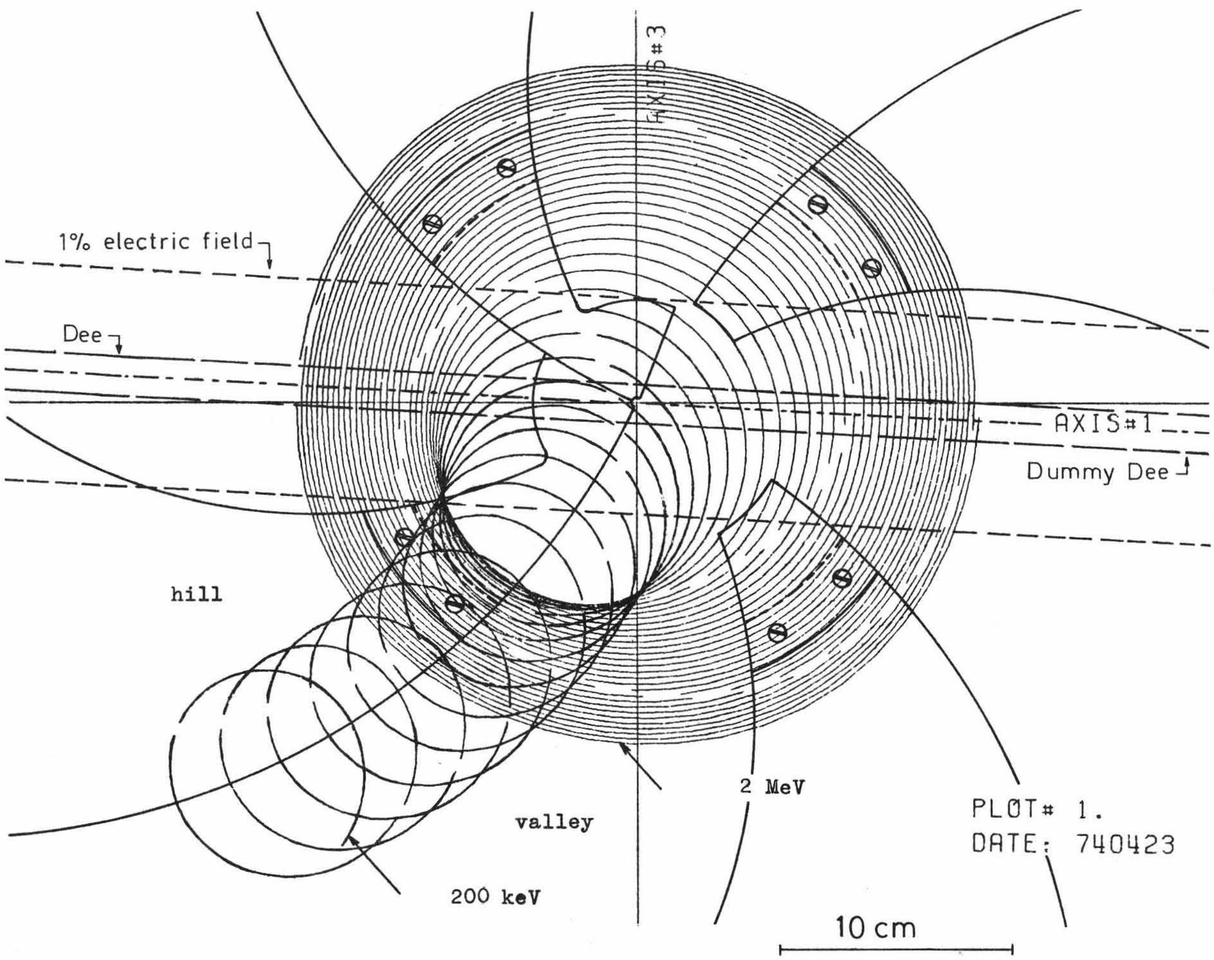

Fig. 3. The horizontal motion of a particle which moves from the precession mode into the central mode.

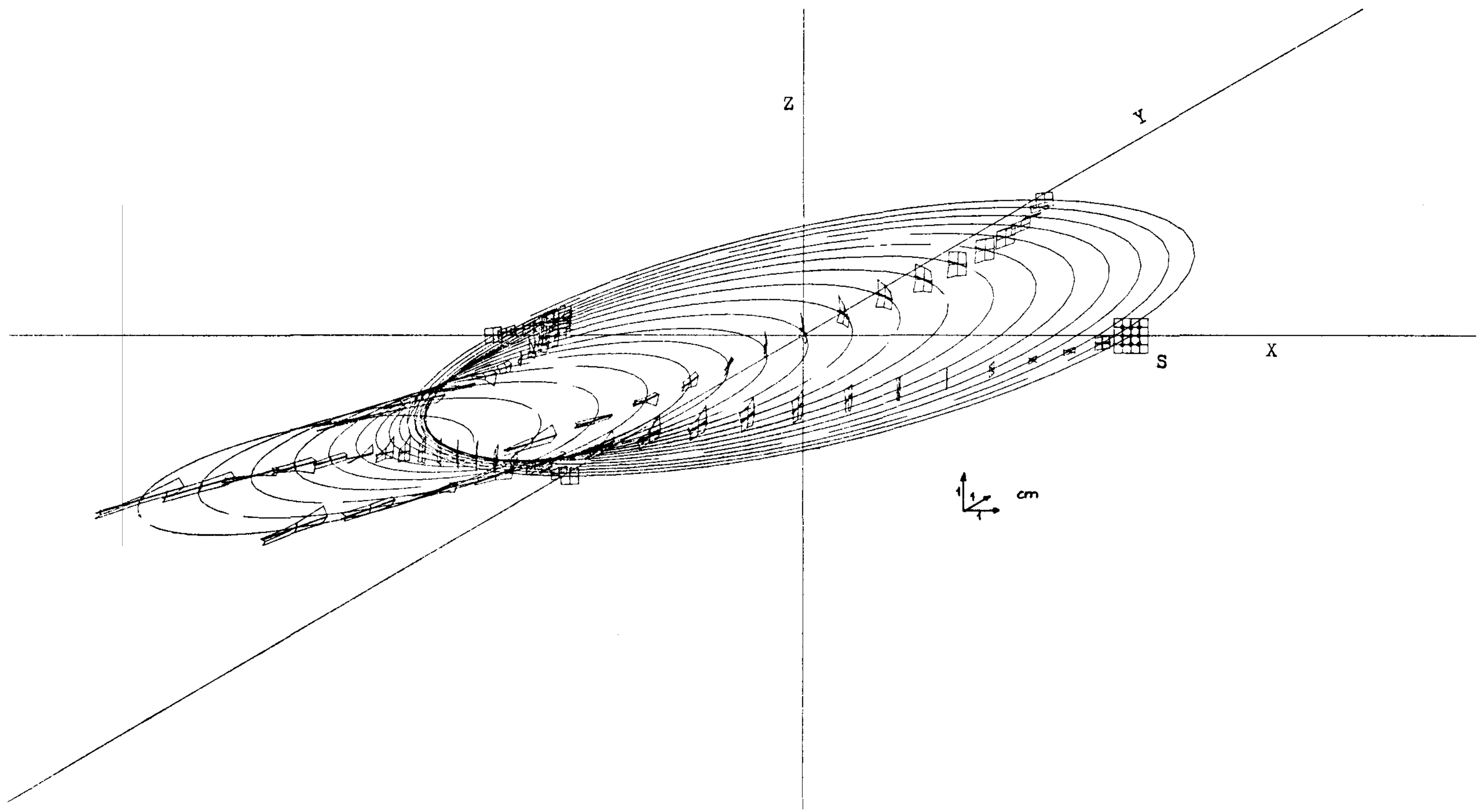

Fig. 4. Stereometric plot (computer program PLPROC) of nine particles coming from the precession motion into the central motion. The solid line depicts the orbit of the centre of gravity of the nine particles, which moves in the median plane. The small wire mats depict subsequent positions of individual particles. Trajectories have been computed (computer program CYCLES) by integrating backwards in time. Three particles have their initial positions above the median plane, three in and three under the median plane at S. All particles have different initial momenta. Original plot is at scale 1:1.

Computer analysis

Computer analysis, first with data obtained from measurements in a 2.5 scaled down magnet model, later with data from the modified cyclotron magnet showed in both cases a gradual transition of precession motion into central motion and the existence of vertical stability (fig. 3 and 4). It also proved to be not necessary to apply a specially shaped dee field. This means that a dee which is straight over the entire accelerating gap can be used.

Curves of the values of fourier coefficients obtained from a fourier analysis of the modified cyclotron field are shown in fig. 5.

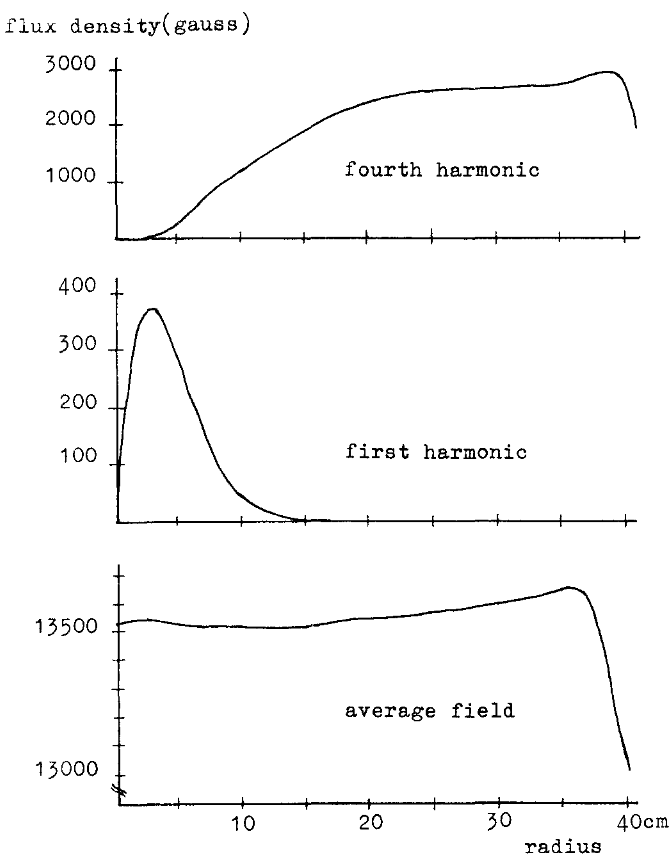

Fig. 5. Results of a Fourier analysis of measurement data from magnetic field with an azimuthal period of 2π. Note the difference in scales of magnetic flux density.

A strong first harmonic component is present at small radii which disappears with larger radii. We found that the fourth harmonic was not much affected compared with the original field. A cause of concern was the mean magnetic field, which we wanted to keep at the value giving the cyclotron frequency. It took several magnet modifications to bring the first harmonic at the desired value while keeping the mean magnet field right.

Coupling mechanism

The coupling mechanism may be described more aptly if the beam is followed backwards in time, this being a possibility which we used extensively in our computer studies. Starting with a beam of e.g. 3 MeV, this beam will be in the normal mode and be decelerated in a field with normal, in our case fourfold symmetry. During further deceleration the mean radius of the beam orbit will decrease and a first harmonic will appear in the magnet field, bringing about a shift in the mean centre of the orbit. It will depend on the phase of this first harmonic in which direction the shift will take place. As deceleration is getting on, the centre of the orbit moves away from the dee gap. Now, if the mean value of the magnetic field over a revolution remains constant, the particles in the beam will remain in phase with the dee field, i.e. when a particle would be decelerated

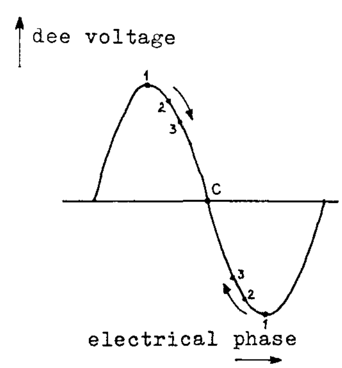

Fig. 6. Particles in the normal motion crossing the accelerating gap at (1) will cross the gap when they are partly in the precession motion at (2), (3) and so on with C as point of symmetry, see text.

at the tops of the dee voltage, subsequent gap crossings would take place at lower voltages but symmetric in time with regard to the zero crossing of the dee voltage, cf. fig. 6. This constitutes a nice bonus because in this way the the mean shift of the centre of curvature brought about by the gap field will be zero, which means that the mean shift of the beam position will be governed by the magnetic field only. Another consequence of the right mean field is that the beam will have the required initial conditions to enter the precession mode where lines of equal flux density will be followed, at a mean magnetic field giving optimum vertical stability. As we chose our nominal precession path with the aim of optimum vertical stability, which coincided with mean cyclotron leadfield and optimum precession velocity, a lot of work was saved in that it was not necessary to redesign our already realised first inflector system.

Results

June this year our cyclotron had been reassembled after the new magnet central region and a new dee with a straight dee edge were built in. The first proton beam injected was also accelerated up to 3 MeV. After a few days which were mainly used to get accustomed to the system, we had the beam at extraction radius and automated shadow measurements were started. We made more than 100 μA at the extraction radius of 38 cm (12 MeV) with an injected beam, measured before the inflector of between 1 and 2 mA.at 200 keV. The system behaves very well, while it is extremely convenient to have all the injection gear outside the cyclotron.

In the central region correction coils have been built which can give small corrections in the magnet field. The injection process functions well without any coil energized. When the coils are energized for optimum beam yield, about 30% more beam is accelerated. Beam current is constant over the normally measured interval of 20 cm radius up to the extraction radius of 38 cm.

Data from shadow measurements are shown in fig. 7, from which coherent and incoherent horizontal betatron amplitudes may be derived [3] of 4 mm and 16 mm.

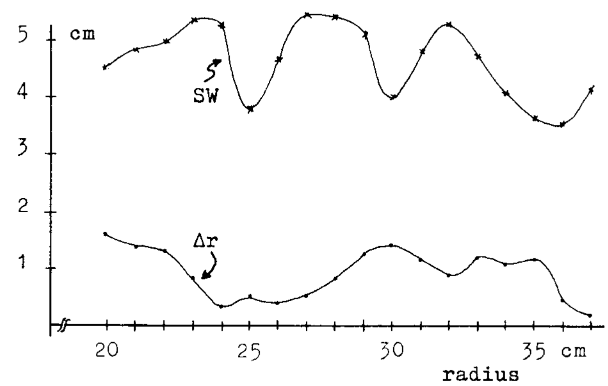

Fig. 7. Shadowwidth (SW) and difference in radial positions of probes (Δr), as a function of pole radius. Probes have an azimuthal difference of 90 degrees, $\nu_r \sim 1.01$.

Our cyclotron is a constant energy machine designed for protons only. Yet we tested the injection system with H_3^+ and acceleration at the third harmonic. A result we obtained was 4 μA of H_3^+ with an injected beam of 400 μA up to a pole radius of 15 cm, while the beam was accelerated up to 25 cm.

Conclusion

It may be expected, that the injection method described here will constitute an attractive alternative for other known injection methods. In our point of view, the large particle yield which has been demonstrated makes a cyclotron a realistic proposition in which only an external ion source is provided for. Such a cyclotron has no deflecting structures at the centre and could have outstanding vacuum properties, making it suitable for the (pre)acceleration of heavy ions.

1) V.A.Gladishev et al., Plasma Physics 8 (1966) p. 199-206.
2) D.J.Clark, Proc.Fifth Intern.Cycl.Conf. (1969) p. 594.
3) H.W.Schreuder, Nucl.Instr.and Meth. 95 (1971) p. 237-244.

DISCUSSION

W. JOHO: How easy is it to use your beautiful injection system for other ions, especially for heavy ions?

W.A. VAN KAMPEN: We did inject $^3H^+$ just for fun, because our pre-accelerator gives also $^3H^+$ of course. We had 400 µA injected and 4 µA up to half the radius. But our machine is only designed for protons, it was just to have this injection scheme with another ion. I think that there are no essential difficulties if you want to accelerate other heavy ions. I do not think there will be a problem because you can scale the whole thing down so that you have the same beam orbit along your precession motion. We did not have many difficulties with the injected beams, it went along fine.

H.W. SCHREUDER: Could you comment on beam centring and beam quality?

W.A. VAN KAMPEN: We have made some shadow-width measurements with 2 probes which were 90° apart. The shadow is not very small. It comes down to 4 mm of coherent oscillation amplitude and about 16 mm of incoherent oscillation. But it is now the only problem we have, because all the other parameters can be changed over a wide range: for example, the vertical position of the beam, the acceleration frequency or the magnetic field. Therefore, what we have to optimize now is the horizontal motion of the beam.

H.G. BLOSSER: You inject a d.c. beam which gives a broad-phase group. If you looked at a narrow-phase group, the shadows should get much sharper?

W.A. VAN KAMPEN: Yes, that will be the case. We also swept the beam a little bit within the acceptance of the inflector and we get about 30% more beam, so you can do things with it: you can have a buncher, for example, or you can cut out things, because there is a lot of beam. We put now into the system 1 or 2 mA, we also have an injector capable of delivering 20 mA, so you can have very narrow widths in the cyclotron.

H.G. BLOSSER: But the centring is dependent on the RF voltage; if it is good for some voltage it will be bad for the phase shift.

W.A. VAN KAMPEN: Yes, this might be the problem.

J.A. MARTIN: What was the efficiency of acceptance of beam into accelerated orbits?

W.A. VAN KAMPEN: We put in 1-2 mA d.c. and we had 110 mA at extraction radius.

J.A. MARTIN: That gives between 5 and 10% including the phase acceptance?

W.A. VAN KAMPEN: Yes, there are other figures, such as 7.5% and 8%. We can say between 5 and 10%.